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## ELECTROWEAK SYMMETRY BREAKING BY EXTRA DIMENSIONS

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Electroweak symmetry breaking may be naturally induced by the observed quark and gauge fields in extra dimensions without a fundamental Higgs field. We show that a composite Higgs doublet can arise as a bound state of  $(t, b)_L$  and a linear combination of the Kaluza-Klein states of  $t_R$ , due to QCD in extra dimensions. The top quark mass depends on the number of active  $t_R$  Kaluza-Klein modes, and is consistent with the experimental value.

Understanding the origin of electroweak symmetry breaking is currently one of the most important questions in particle physics. In the Standard Model (SM), it is assumed that there exists a fundamental scalar Higgs field with a negative squared mass, whose vacuum expectation value (vev) breaks the electroweak symmetry. However, the mass squared of a fundamental scalar field receives a quadratic divergent contribution from radiative corrections, therefore suffers from the “hierarchy problem” if the cutoff scale is much higher than the weak scale. Recently, a new solution to the hierarchy problem has been proposed by postulating the existence of large extra dimensions.<sup>1</sup> In that case, the fundamental scale (which is assumed to be the cutoff scale) in the higher dimensional theory can be reduced to the TeV range and hence it removes the large hierarchy between the weak scale and the Planck scale. However, just removing the large hierarchy, while avoiding the fine-tuning problem, does not explain why the electroweak symmetry is broken, *i.e.*, why there is a Higgs field and why its squared mass is negative. Here we point out that the extra dimensions can also provide a natural mechanism for electroweak symmetry breaking without introducing a fundamental Higgs field.

In fact, a composite Higgs field can arise in the presence of certain strongly coupled four-quark operators.<sup>2</sup> These four-quark operators are naturally induced by the Kaluza-Klein (KK) excitations of the gluons if QCD lives in compact extra dimensions.<sup>3</sup> The strength of these contact interactions depends on the ratio of the compactification scale,  $M_c$ , and the fundamental scale  $M_s$  of

the quantum gravitational effects which cuts off the higher dimensional gauge interactions. It has been argued that the SM gauge couplings can unify in the presence of extra dimensions due to the accelerated power-law running.<sup>4</sup> Assuming that they unify at  $M_s$ , one typically finds that the gauge couplings already become strong at that scale for more than two extra dimensions. Thus, it is possible that the non-perturbative effects form a composite Higgs out of the quarks.

The simplest 4-dimensional top-condensate model of a composite Higgs predicts a too large top-quark mass, of approximately 500 – 600 GeV, if the compositeness scale is not much higher than the weak scale.<sup>2</sup> For a viable composite Higgs model, some vector-like quarks are required to participate in the binding mechanism together with the top quark.<sup>5</sup> They should have the same SM quantum numbers as the top quark, so they can naturally be identified as the KK excitations of the top quark in a theory with extra dimensions.<sup>6</sup> For instance, if we assume that only the right-handed top lives in extra dimensions, the Higgs doublet will be a bound state of the left-handed top-bottom doublet ( $\psi_L$ ) and a linear combination of the KK modes of  $t_R$ ,

$$H \sim \psi_L \sum_{i=0}^{n_{\text{KK}}-1} \chi_R^i, \quad (1)$$

where  $\chi_R^0 = t_R$ . The top quark mass will be suppressed by  $1/\sqrt{n_{\text{KK}}}$  compared with the prediction of the simplest top condensate model. For a typical  $n_{\text{KK}} \sim 10 - 30$ , the top Yukawa coupling is around 1, in agreement with the experimental result.

We now present a model for concreteness. This is not a unique choice, but just an illustrative example of the idea. We assume that SM gauge fields propagate in  $\delta$  compact extra dimensions, whose coordinates are labeled by  $y, z_1, \dots, z_{\delta-1}$ , with sizes  $L$  and  $L_z (\ll L)$  respectively. The  $t_R$  is the zero mode of a 5-dimensional fermion  $\chi$ , which is fixed at  $z = 0$ , but propagates on the  $[0, L]$  interval in the  $y$  direction, while the  $\psi_L = (t, b)_L$  is fixed at  $z = 0$  and  $y = y_0$ . (See Fig. 1.) The absence of a left-handed zero mode of  $\chi$  can result from some boundary condition such as the  $S_1/Z_2$  orbifold projection. For simplicity, we assume that all other quarks are 4-dimensional fields with left- and right-handed quarks localized at different positions in extra dimensions so that they do not form bound states.

Because  $L_z \ll L$ , we first integrate out the  $z$  directions below the scale  $L_z^{-1}$  and obtain a 5-dimensional effective theory. The 4-quark interactions are induced by the KK gluons in the  $z$  directions. After a Fierz transformation,

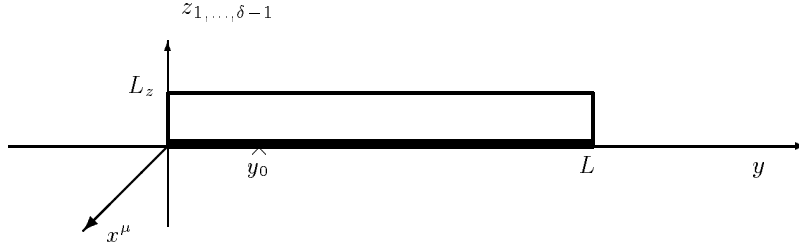


Figure 1:  $x^\mu$  are coordinates of the flat four-dimensional spacetime,  $z_1, \dots, z_{\delta-1}$  are the dimensions accessible only to the gauge bosons,  $\chi$  propagates on  $0 \leq y \leq L$ , and  $\psi_L$  is located at the point marked on the  $y$  axis.

the 4-quark interactions at the compositeness scale  $\Lambda$  are given by

$$\frac{cg_5^2}{\Lambda^2} \left\{ \delta(y - y_0) (\bar{\psi}_L \chi) (\bar{\chi} \psi_L) + \frac{5}{16} \left[ (\bar{\chi} \chi)^2 - \frac{1}{3} (\bar{\chi} \gamma_5 \chi)^2 \right] \right\} + \dots, \quad (2)$$

where  $c \gg 1$  represents the effect of summing over gluon KK modes, and the ellipsis stand for vectorial and tensorial four-quark operators, which are not relevant at low energies.

From eq. 2 one can see that the attractive interactions can give rise to the following bound states: a 4-dimensional weak doublet complex scalar,  $H(x^\mu) \sim \bar{\chi} \psi_L$ , and a 5-dimensional gauge singlet real scalar,  $\varphi(x^\mu, y) \sim \bar{\chi} \chi$ . They obtain non-zero kinetic terms in running down to low energies and become dynamical fields. They also receive large negative contributions to their squared masses. Electroweak symmetry is broken when the squared mass of the composite Higgs becomes negative. Decomposing  $\chi$  into 4-dimensional KK states, one can see indeed that the Higgs field is a bound state of the doublet  $\psi_L$  and a linear combination of the KK modes of  $t_R$ . Since the observed (right-handed) top quark is only one of the  $n_{\text{KK}}$  states which participate in the electroweak symmetry breaking, the top Yukawa coupling is adequately suppressed by  $1/\sqrt{n_{\text{KK}}}$  as mentioned above.

Whether the singlet  $\varphi$  affects the low energy physics at the weak scale depends on the setup. To illustrate this we consider two special cases. First, if  $\psi_L$  is located at the boundary ( $y_0 = 0$ ), the Higgs is more strongly bound and hence  $\varphi$  will remain heavy when  $m_H^2$  becomes negative. There is no mixing between  $H$  and  $\varphi$  because  $\varphi$  vanishes at the boundary. The low energy theory is simply the Standard Model with a composite Higgs boson which is expected to be heavy. It can still be consistent with the electroweak precision measurements because of the mixings between  $t, W, Z$  and their KK states.<sup>7</sup>

Another interesting case is that  $\psi_L$  is localized in the middle of the  $0 < y < L$  interval. In this case, the attractive interactions in the  $H$  and  $\varphi$  channels are comparable, therefore both can obtain non-zero vevs. The mixing between  $H$  and  $\varphi$  can make either the Higgs boson or the singlet light. If the mass of the lightest singlet is less than half of the Higgs mass, the Higgs boson may decay predominantly into two  $\varphi$ 's, which subsequently decay into two gluons or two photons through the top loop, because the Higgs boson interacts strongly with  $\varphi$ . This will modify the Higgs search at future colliders.

The model we have summarized here represents a minimal model in extra dimensions. The only fields present at the fundamental scale are the standard fermions and gauge bosons in the higher dimensional spacetime. It is remarkable that at energies below the compactification scale this simple theory reproduces the Standard Model, with the possible addition of a light singlet scalar. We emphasize though that there is need for flavor violating operators at the fundamental scale in order to generate masses for the quarks (other than top) and leptons. These operators induce Yukawa couplings at low energy. Therefore the fermion masses are accommodated as in the SM without theoretical predictions other than the top mass.

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